Renewable and Sustainable Energy Reviews 27 (2013) 853–863

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comparative study of total, direct and diffuse solar irradiance by using different models on horizontal and inclined surfaces for Cairo, Egypt

Samy A. Khalil [a,*], A.M. Shaffie [b,1]

[a] National Research Institute of Astronomy and Geophysics, Solar and Space Department, Marsed Street, Helwan, 11421 Cairo, Egypt
[b] Egyptian Meteorological Authority (EMA), P.O. Box 11784, Cairo, Egypt

ARTICLE INFO

Article history:
Received 6 November 2012
Received in revised form
21 June 2013
Accepted 24 June 2013
Available online 27 August 2013

Keywords:
Solar radiation
Modeling
Isotropic models
Anisotropic models
Inclined surface

ABSTRACT

The measured hourly daily data of total, direct and diffuse solar irradiation incident on a horizontal and an inclined surface for Cairo, Egypt (Lat. 30°05′N and Long. 31°15′E), during the period (1990–2010) are analyzed. The regression equations between (G/G_o) and meteorological variables along with the values of MBE, RMSE, MPE, R^2 and the t-test statistics are summarized in this research. The values of correlation coefficients (R^2) are higher than 0.95 and the values of the RMSE are found in the range 3.13–6.34, thus indicating a good agreement between measured and calculated values of the total solar radiation (G). The models of Eqs. (10), (11) and (14) have well estimated the total solar irradiation in the selected location during the time period in the present study. For all models, the absolute values of the MPE indicate very good agreement between measured and calculated values of the diffuse solar fraction (G_d/G) or the diffuse solar transmittance (G_d/G_o) and clearness index K_t, relative number of sunshine hours (S/S_o) and their combination. The models of Hay (Ha), Skartveit and Olseth (SO) and Perez et al. (P9) give the most accurate predictions for the south-facing surface, and Hay (Ha) and Perez et al. (P9) models performs better as estimated for the west-facing surface.

Contents

1. Introduction . . . 854
2. Instrumentations and climate site . . . 854
3. Solar radiation basic . . . 855
   3.1. Computing the semi-hourly total extraterrestrial solar radiation G_{oh} . . . 855
   3.2. Zenith azimuthal and hour angles . . . 855
4. Modeling of solar energy . . . 855
   4.1. Global solar energy models on horizontal surface . . . 855
   4.2. Computing beam and diffuse radiation on horizontal surface . . . 855
   4.3. Global solar energy models on inclined surface . . . 856
   4.4. Diffuse solar energy models on inclined surface . . . 857
5. Comparison techniques of modeling . . . 858
   5.1. Mean Bias Error (MBE) . . . 858
   5.2. Root Mean Square Error (RMSE) . . . 858
   5.3. The t-test statistic (t) . . . 858
   5.4. The correlation coefficient (R^2) . . . 858
6. Results and discussion . . . 858
7. Conclusion . . . 861
References . . . 862

* Corresponding author. Now at: Department of Physics, Faculty of Science, Al-Baha University, Kingdom of Saudi Arabia. Tel.: +20 225560645; fax: +20 225548020.
E-mail addresses: samynki@yahoo.com (S.A. Khalil), shaffie_2006@yahoo.com (A.M. Shaffie).
[1] Now at: Department of Physics, Faculty of Science, Al-Baha University, Kingdom of Saudi Arabia.

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.06.038

1. Introduction

Solar irradiation is measured at many locations around the globe. Unfortunately, these locations are mainly concentrated in developed countries, and are scarce within the developing world; solar irradiation data are fundamental inputs for solar energy applications such as photovoltaics, solar thermal systems, and passive solar design. Daily data on horizontal and tilted surface are required for day-to-day performance monitoring in applications such as solar gains from vertical glazing, day lighting and agricultural processes; these data are also useful to engineers in designing of various solar energy conversion devices and accurate modeling of the impact of solar gains through glazing which is imperative especially when simulating the thermal behavior of these buildings. Empirical validations of solar gain models are therefore an important and necessary endeavor to provide confidence to developers and modelers that their respective algorithms simulate reality [1–3].

Solar energy consists of two parts: extraterrestrial solar energy which is above the atmosphere and global solar energy which is under the atmosphere. The measured solar energy values can be used for developing solar energy models which describe the mathematical relations between the solar energy and the meteorological variables such as ambient temperature, humidity and sunshine ratio. These models can be later used to predict the direct and diffuse solar energy using historical metrological data at sites where there is no solar energy measuring device installed. Solar energy of daylight utilization for any site is dependent upon the quality of the available flux. Obviously, the flux impinging upon any arbitrary surface undergoes monthly as well as diurnal variations. The measurements of solar energy received from the sun, on horizontal as well as on sloped surface, are an expensive affair. As such, few locations in the world have reliable, long-term measured irradiation data sets. Daylight records are even scarcer. Most radiation data are given as the energy received on a horizontal surface. Since only very few applications use this configuration, there is a genuine need for insolation estimation to be carried out for sloped surface of any given aspect; the accuracy of these models varies from 40% to 50% for abbreviated techniques to limits set out by the accuracy of the measuring equipment for modern sophisticated models [4,5]. The total solar radiation on a horizontal surface is called global irradiance and is the sum of incident diffuse radiation plus the direct normal irradiance projected onto the horizontal surface. If the surface is tilted with respect to the horizontal, the total irradiance is the incident diffuse radiation plus the direct normal irradiance projected onto the tilted surface plus ground reflected irradiance that is incident on the tilted surface [6–9].

Many empirical models have been used to estimate solar radiation, utilizing the available data on meteorological [10,11], geographical and climatological parameters. Among these parameters, sunshine duration [12–15], air temperature [16], latitude and longitude [17], precipitation [18], relative humidity [16,19,20], wind speed and cloudiness [21–26] were used. Of these, the most commonly used parameter for estimating total solar radiation is sunshine hours. In this respect, the modified version of Angstrom equation, among various correlations, has been widely used to estimate the total solar irradiation on horizontal surface [27–35].

In most of the solar energy applications, inclined surfaces at different angles are widely employed. The solar irradiance on a horizontal surface has been measured in many meteorological stations around the world, but there are only a few stations that measure the solar component on inclined surfaces [36–38]. There are a number of models available to estimate solar irradiation on inclined surface from corresponding horizontal data. This requires, in general, the availability of detailed information on the magnitude of diffuse and direct horizontal irradiance. A number of diffuse fraction models are available as documented in [39–43]. These models are usually expressed in terms of polynomial functions relating the diffuse fraction to the clearness index. An inclined surface solar irradiation model developed by Olmo et al. [44] requires only the horizontal surface solar irradiation, with incidence and solar zenith angles as input parameters.

Many solar energy models have been presented in the literature using mathematical linear [45–53] and nonlinear functions [54–60], artificial neural network [61–71] and fuzzy logic [72–74]. An important aspect in modeling solar energy is the accuracy of the developed model which is evaluated using statistical errors such as the mean absolute percentage error (MAPE), mean bias error (MBE) and root mean square error (RMSE). The MAPE is an indicator of accuracy in which it expresses the difference between real and predicted values to the real value. The calculated MAPE is summed for every fitted or forecasted point in time and divided again by the number of fitted points; n. MBE is an indicator for the average deviation of the predicted values from the measured data. A positive MBE value indicates the amount of overestimation in the predicted total solar energy and vice versa. On the other hand, RMSE provides information on the short-term performance of the model and is a measure of the variation of the predicted values around the measured data. RMSE also shows the efficiency of the developed model in predicting future individual values [3,71]. A large positive RMSE implies a big deviation in the predicted value from the measured value. Part of this study was used before to evaluate the statistical comparison models of solar energy on horizontal and inclined surfaces [3]; in the present work, the average hourly daily data of solar irradiation models on horizontal surface and various inclined surface in the selected site will be studied, using empirical models which were selected to estimate the solar radiation on horizontal and inclined surfaces.

2. Instrumentations and climate site

In the present work, the global, direct and diffuse solar radiation incident on a horizontal surface at Cairo, Egypt (Lat. 30°05′N and Long. 31°15′E), during the time period from January 1990 to December 2010 is used. The radiation data of the corresponding periods are obtained from the Egyptian Meteorological Authority. The data sets used consist of mean hourly and daily values of global and diffuse solar irradiations on a horizontal plane. Total solar radiation was measured using Eppley high-precision pyranometer responsive at 300–3000 nm, while another precision pyranometer equipped with a special shading device, SBS model, was used to measure diffuse irradiation. The shadow band stand is constructed of anodized aluminum, which weighs approximately 24 lb and uses a 300 band of approximately 2500 diameter to shade the pyranometer. Because the shadow band screens the sensor from a portion of the incident diffuse radiation coming in from the sky, a correction was made to the measurements following Batlles et al. [3,75,76]. Total solar radiation data were recorded by the Eppley Precision Spectral Pyranometer (PSP) at all stations. The accuracy of these pyranometers corresponds to the first class according to the World Meteorological Organization classification [77]. These instruments are calibrated each year against a reference instrument traceable to the World Radiometric Reference (WRR) maintained at Davos, Switzerland [78,79]. According to the calibration certificate of the manufacturers, sensitivity is approximately 9 $\mu V/W/m^2$, temperature dependence is $\pm 1\%$ over ambient temperature range -20 to +49 °C, linearity is $\pm 0.5\%$ from 2800 W/m^2, and cosine is $\pm 1\%$ from normalization 0–70° zenith angle and $\pm 3\%$ for 70–80° zenith angle. The absolute accuracy of calibration is ± 3–4%.

There are few peculiarities in the climate of Egypt that may affect the characteristics of the sough relation, which we shall outline here. Cloud characteristics and air temperature change from one season to another as follows: winter is the season of different cloud types, which are normally opaque to the direct beam, and has minimum temperature, in addition to low turbidity of the atmosphere. Spring is characterized by the passage of small and shallow thermal depressions, inducing what is called Khamasin weather. Vertical visibility is deteriorated progressively with increasing dust content in the lower layers. After the passage of these depressions, clouds form and horizontal visibility is reduced much in the atmosphere. In summer, high temperature, high transparency and semi-transparent clouds prevail, but despite their existence, the sky is 'dirty' most of the time, due to deep layers of fine dust particles associated with continental tropical air. The dust content falls markedly when Mediterranean air arrives, associated with fine weather cumulus. In autumn, the atmosphere is fairly transparent on average. Morning mists and low clouds dissipate after sunrise [3,80].

3. Solar radiation basic

3.1. Computing the semi-hourly total extraterrestrial solar radiation G_{oh}

Solar radiation incident outside the earth's atmosphere is called extraterrestrial solar radiation. On average the extraterrestrial irradiance is 1367 W/m^2 (solar constant). The extraterrestrial radiation G_{oh} is given as follows [3,81]:

$$G_{oh} = (24/\pi) \times I_{SC} \times E_o[\cos\varphi \cos\delta \sin\omega + (\pi\omega/180)\sin\varphi \sin\delta] \quad (1)$$

where E_o is the correction factor of the Earth's orbit and ω is the sunrise/sunset hour angle given respectively by

$$E_o = 1 + 0.033\cos(2\pi dn/365), \quad (2)$$

$$\omega = \cos^{-1}(-\tan\varphi \tan\delta) \quad (3)$$

where φ is the latitude and the solar declination angle of the sun (δ) is the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis, which is given in degrees according to Spencer [82] as

$$\delta = (0.006918 - 0.399912\cos\Gamma + 0.070257\sin\Gamma - 0.006758\cos2\Gamma + 0.000907\sin2\Gamma - 0.002697\cos3\Gamma + 0.00148\sin3\Gamma)(180/\pi) \quad (4)$$

where Γ is the day angle in radiance, and it is represented by

$$\Gamma = 2\pi(d_n - 1)/365 \quad (5)$$

where d_n is the day of the year.

3.2. Zenith azimuthal and hour angles

To describe the sun's path across the sky one needs to know the angle of the sun relative to a line perpendicular to the earth's surface which is called the zenith angle (θ) and the angle of the sun's position relative to the north–south axis is the azimuthal angle (α). The hour angle (ω) is easier to use than the azimuthal angle because the hour angle is measured in the plane of the "apparent" orbit of the sun as it moves across the sky (Fig. 1) [3,6]. With the above information, one can calculate the cosine of the zenith angle as follows:

$$\cos(Z) = \cos(\varphi)\cos(\delta)\cos(\omega) + \sin\varphi \sin\delta \quad (6)$$

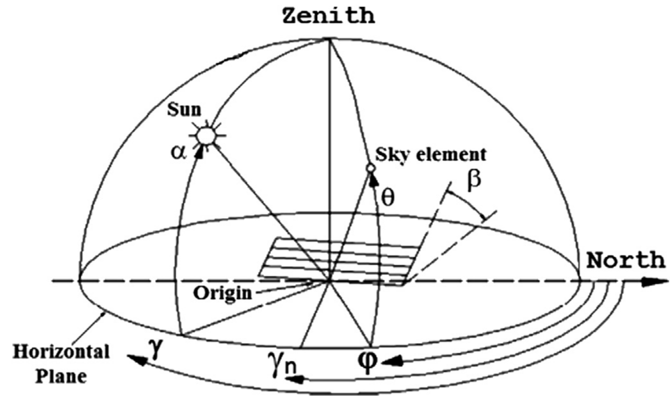

Fig. 1. Zenith, azimuthal, and hour angles.

4. Modeling of solar energy

The commonly used solar energy models developed in the past are based on linear and nonlinear models [83]. These models give a correlation between solar energy on a horizontal surface and some meteorological variables such as shine hours s, ambient temperature T, cloud cover c_w, relative humidity R_h, and maximum $T_{max.}$ and $T_{min.}$ ambient temperatures. The linear models use simple linear function while the nonlinear models are polynomial functions of the third or fourth degree.

4.1. Global solar energy models on horizontal surface

Linear and nonlinear models can be used to calculate the total solar energy in terms of sunshine hours. A commonly used linear model for this purpose which defines the total solar energy in terms of the extraterrestrial solar energy is given [3,5,84] as follows:

$$G/G_o = a + b(s/s_o) \quad (7)$$

$$G/G_o = a + b(s/s_o) + c(s/s_o)^2 \quad (8)$$

$$G/G_o = a + b(s/s_o) + cT \quad (9)$$

$$G/G_o = a + b(s/s_o) + cR_h \quad (10)$$

$$G/G_o = a + bT + cR_h \quad (11)$$

$$G/G_o = a + b(T_{max.} - T_{min.}) + cc_w \quad (12)$$

$$G/G_o = a + b(T_{max.} - T_{min.})^{0.5} + cc_w \quad (13)$$

$$G/G_o = a + b(s/s_o) + cc_w \quad (14)$$

$$G/G_o = a + b(s/s_o)^c \quad (15)$$

where a, b and c are the empirical constants and s_o is the maximum possible monthly average daily sunshine duration or the day length.

4.2. Computing beam and diffuse radiation on horizontal surface

The empirical correlations for calculating the average hourly daily diffuse radiation incident on a horizontal surface, the diffuse fraction (G_d/G) and diffuse transmittance (G_d/G_o) were correlated to first, second and third order correlations of the clearness index (K_t) and the relative number of sunshine hours (S/S_o) [3,57]. It is found that the second and third order correlations do not improve the accuracy of estimation of (G_d). Therefore, the following

correlations have been obtained for Cairo:

$$G_d/G = 5.817–6.517K_t,\ R^2 = 0.972 \quad (16)$$

$$G_d/G = 8.342–6.455(S/S_0),\ R^2 = 0.958 \quad (17)$$

$$G_d/G_o = 3.815–5.319(S/S_0),\ R^2 = 0.932 \quad (18)$$

$$G_d/G_o = 4.912–6.894K_t,\ R^2 = 0.985 \quad (19)$$

Furthermore, (G_d/G) and (G_d/G_o) were correlated to the first and second order correlations of the (K_t) and (S/S_o) combination. Also, it has been found that the second order correlations between (G_d/G) or (G_d/G_o) and (K_t) and (S/S_o) combination do not improve the accuracy of estimation of (G_d). The following correlations were found to fit the measured data of (G_d):

$$G_d/G = 6.314–5.131K_t + 0.136(S/S_0),\ R^2 = 0.982 \quad (20)$$

$$G_d/G_0 = 5.292–4.226K_t–0.321(S/S_0),\ R^2 = 0.991 \quad (21)$$

Eqs. (16)–(21) were used to calculate (G_d) and the obtained results were compared with the measured values of (G_d). The accuracy of estimating (H_d) was checked by calculating the MBE, RMSE, MPE, R^2 and the t-test.

A simple, physically based method proposed in [3,85,86] was used for estimating hourly diffuse and direct components from hourly total irradiance. For three different ranges of atmospheric transmissivity ($K_t = G_h/G_{oh}$), the resulting correlations are given by the following expression:

$$D_h/G_h = \begin{cases} 0.995-0.081K_t & \text{if } K_t < 0.21. \\ 0.724 + 2.738K_t - 8.32K_t^2 & \text{if } 0.21 \le K_t \le 0.76. \\ 0.180 & \text{if } K_t > 0.76. \end{cases} \quad (22)$$

Then, we can calculate the value of the hourly direct solar radiation as follows:

$$B_h = G_h - D_h \quad (23)$$

4.3. Global solar energy models on inclined surface

The knowledge of the solar total radiation incident on such a tilted surface is a prerequisite for the design of cost effective systems. The amount of elevation from the horizontal, the tilt angle, should be equal to the latitude angle of the location of the collector. This orientation is often selected for flat-plate collector installations, since it averages the installation peaks over the year. The surface axis tilted from the horizon by the latitude angle toward the south, is called an equatorial mounting. This is the ideal way of setting up the collectors. It is also the easiest and cheapest [3,10].

The total solar irradiation on a horizontal surface has been measured in many meteorological stations around the world, but there are only a few stations that measure the solar component on inclined surfaces. There are a number of models available to estimate solar irradiation on an inclined surface from the radiation on a horizontal surface, but these models require knowledge of the total irradiation, direct or diffused irradiation or reflected irradiation on a horizontal surface. An inclined surface solar irradiation model developed by Olmo et al. [3,10,44] requires only the horizontal surface solar irradiation, with incidence and solar zenith angles as input parameters.

The Olmo et al. [3,44] model was developed to estimate the solar radiation on inclined surfaces using the data collected on horizontal surfaces. This model depends on the clearness index and avoids the direct and diffused solar radiation components. In the case of no ground reflections, the Olmo et al. model estimates the global irradiance (G_β) on an inclined surface from the corresponding solar radiation (G) on a horizontal surface by the following equation:

$$G_\beta = G\psi_o \quad (24)$$

where β is the surface inclination angle and Ψ_o is a function that converts the horizontal solar radiation to that incident on a tilted surface and is given as

$$\psi_o = \exp[-K_t(\theta^2 - \theta_z^2)] \quad (25)$$

where θ and θ_z (in radians) are the incidence and solar zenith angles, respectively, and K_t is the hourly clearness index.

Further, Olmo et al. [44] proposed a multiplying factor (F_c) to take into account anisotropic reflections and it is given as

$$F_c = 1 + \rho \sin^2(\theta/2) \quad (26)$$

where ρ is the albedo of the underlying surface; this is the most commonly used expression for the radiation reflected from the ground. In this work a constant value for the albedo is used equal to 0.2.

The Olmo et al. model for determining the global solar radiation on an inclined surface from that on a horizontal surface is then

$$G_\beta = G\psi_o F_c \quad (27)$$

The hourly total solar irradiance incident on a tilted surface (G_{Th}) can be divided into three components: the beam component from direct irradiation of the tilted surface (B_{Td}) and the ground reflected (R_{Th}) and sky-diffuse (D_{Th}) components:

$$G_{Th} = B_{Th} + D_{Th} + R_{Th} \quad (28)$$

The amount of direct radiation on a surface tilted S degrees from the horizontal and rotated α_T degrees from the north–south axis can be calculated by multiplying the direct horizontal irradiation by the ratio of cos θ/cos Z, where θ is the solar incidence angle on a tilted plane and Z is the solar zenith angle. Also, the measuring station was located on a roof-top with very low reflectance, and the reflected component was very much lower than the direct and the diffuse components so an isotropic model can be used to compute the reflected component on the tilted surface. So, Eq. (28) can be written again as follows:

$$G_{Th} = B_h \cos(\theta)/\cos(Z) + R_d D_h + G_h\rho[1-\cos(S)]/2 \quad (29)$$

where B_h, D_h and G_h are the hourly direct, diffuse and total solar radiation on a horizontal surface, either measured directly or estimated from each other, R_d is the ratio of the hourly diffuse irradiation incident on a tilted surface to that on a horizontal surface, ρ is the ground reflectivity equal to 0.2 as assumed here because of the lack of a specific measurement, Z is defined from Eq. (6) and θ is calculated by the formula [86]:

$$\cos(Z) = \sin(S)\sin(Z)\cos(\alpha S - \alpha T) + \cos(S)\cos(Z) \quad (30)$$

Several published meteorological data give the total solar radiation on horizontal surfaces; correlation procedures are required to obtain insolation values on tilted surfaces from horizontal radiation. Monthly average daily total radiation on a tilted surface (G_T) is normally estimated by individually considering the direct beam (G_B), and diffuse (G_D) and reflected components (G_R) of the radiation on a tilted surface. Thus for a surface tilted at a slope angle from the horizontal, the incident total radiation is given by the relation:

$$G_T = G_B + G_D + G_R \quad (31)$$

Several models have been proposed by various authors [3,6,30–35,87–89] to calculate solar radiation on tilted surfaces from the available data on a horizontal surface. The only difference among the models appears in the assessment of sky-diffuse component. Based on the assumptions made, the estimation models can be

classified into isotropic [90] and anisotropic [87,88] ones. The daily beam radiation received on an inclined surface can be expressed as

$$G_B = (G_g - G_d)R_b \tag{32}$$

where G_g and G_d are the monthly mean daily global and diffuse radiation on a horizontal surface, and R_b is the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface. The daily ground reflected radiation can be written as

$$G_R = G_g\rho\frac{(1-\cos\beta)}{2} \tag{33}$$

where β is the tilt angle of the solar panel. Liu and Jordan [6,89] have suggested that R_b can be estimated by assuming that it has the value which would be obtained if there was no atmosphere. For surfaces in the northern hemisphere, sloped towards the equator, the equation for R_b is given as [89]

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\sin\omega_{SS} + \omega_{SS}\sin(\varphi-\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_{SS} + \omega_{SS}\sin\varphi\sin\delta} \tag{34}$$

where ω_{SS} is the sunset hour angle for tilted surface for the mean day of the month, given by Eq. (3). For surfaces in the southern hemisphere, sloped towards the equator, the equation for R_b is given as follows:

$$R_b = \frac{\cos(\varphi+\beta)\cos\delta\sin\omega_{SS} + \omega_{SS}\sin(\varphi+\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_{SS} + \omega_{SS}\sin\varphi\sin\delta} \tag{35}$$

and then, the total solar radiation on a tilted surface can be expressed as follows:

$$G_T = (G_g - G_d)R_b + G_g\rho\frac{(1-\cos\beta)}{2} + G_dR_d \tag{36}$$

As no information is available on ground albedo, ρ values are assumed to be 0.2; according to Eq. (36), we need the direct and diffuse components of global radiation for the estimation of global solar radiation on tilted surfaces [6].

4.4. Diffuse solar energy models on inclined surface

The models used to estimate the ratio of diffuse solar radiation on a tilted surface to that on a horizontal surface are classified as isotropic and anisotropic models. The isotropic models assume that the intensity of diffuse sky radiation is uniform over the sky dome. Hence, the diffuse radiation incident on a tilted surface depends on the fraction of the sky dome seen by it. The anisotropic models assume the anisotropy of the diffuse sky radiation in the circumsolar region (sky near the solar disk) plus an isotropically distributed diffuse component from the rest of the sky dome. The sky-diffuse solar radiation can be expressed as

$$G_d = R_dG_d \tag{37}$$

where R_d is the ratio of the average daily diffuse solar radiation on a tilted surface, to that on a horizontal surface; the diffuse solar radiation models chosen in the present study are as follows [3,6,30].

The isotropic sky model [4,91–93] is the simplest model that assumes all diffuse solar radiation is uniformly distributed over the sky dome, i.e., it is independent of the azimuth and zenith angles. It approximates the completely overcast sky condition. The formula for the hourly sky diffuse solar radiation incident on an inclined plane is given by the product of the hourly diffuse solar radiation incident on a horizontal surface and the configuration factor from the surface to the sky, $(1+\cos\beta)/2$. For the surface tilted by an angle β from the horizontal plane, the total solar irradiance can be written as follows:

$$G_{d,T} = G_{d,H}\frac{(1-\cos\beta)}{2} \tag{38}$$

The isotropic model is given by the Badescu model (Ba) [94] as follows:

$$R_d = \frac{3+\cos(3\beta)}{4} \tag{39}$$

The Tian et al. model (Ti) [95] is given by the relation:

$$R_d = 1-\beta/180 \tag{40}$$

The Koronakis model (Kr) [96] is given as follows:

$$R_d = 1/3[2+\cos(\beta)] \tag{41}$$

The Liu and Jordan (LJ) model [90] is given as follows:

$$R_d = \frac{1+\cos\beta}{2} \tag{42}$$

In addition to isotropic diffuse and circumsolar radiation, the Reindl model also accounts for horizon brightening [97,98] and employs the same definition of the anisotropic model.

The Reindl et al. model (Re) [98] is given by the relation:

$$R_d = (G_b/G_o)R_b + \left[1-(G_b/G_o)\left[\frac{(1+\cos\beta)}{2}\right]\left[1+\sqrt{(G_o/G_g)}\sin^3(\beta/2)\right]\right] \tag{43}$$

The Skartveit and Olseth model (SO) [99] is given as follows:

$$R_d = (G_b/G_o)R_b + \Omega\cos\beta + \left[1-(G_b/G_o)-\Omega\right]\left[\frac{(1+\cos\beta)}{2}\right] \tag{44}$$

where

$$\Omega = \{\mathrm{Max}[0(0.3-2G_b/G_o)] \tag{45}$$

The Steven and Unswoth model (SU) [100] is given as follows:

$$R_d = 0.51R_b + \frac{1+\cos\beta}{2} - (1.74/1.26\pi)\left[\sin\beta - \beta(\pi/180)\cos\beta - \pi\sin^2(\beta/2)\right] \tag{46}$$

The Hay model (Ha) [91] is given by the relation:

$$R_d = (G_b/G_o)R_b + \left[1-(G_b/G_o)\right]\left[\frac{(1+\cos\beta)}{2}\right] \tag{47}$$

The Klucher model, 1979 (Kl) [101], is based on a study of clear sky conditions by Temps and Coulson [102]; their model was modified by Klucher, who incorporated conditions of cloudy skies. Klucher's formulation of the hourly sky diffuse solar radiation incident on an inclined surface is

$$G_{d,T} = G_{d,g}\left\{\left[\frac{(1+\cos\beta)}{2}\right]\left[1+F_1\sin^3(\beta/2)\right]\left[1+F_1\cos^2\theta_z\sin^3\theta_z\right]\right\} \tag{48}$$

where F_1 is the modulating function given by $F_1=(G_{d,g}/G_g)^2$, when the skies are completely overcast, F=0, Klucher's model reverts to the isotropic model.

The Perez model (Perez et al. [103,104]; P8 and P9 respectively) [4] is more computationally intensive and represents a more detailed analysis of the isotropic diffuse, circumsolar and horizon brightening radiation by using empirically derived coefficients. The total irradiance on the tilted surface is given by the following equation:

$$G_T = G_{h,b}R_b + G_{h,d}\left[(1-F_1)\frac{(1+\cos\beta)}{2} + F_1\frac{a}{b} + F_2\sin\beta\right] + G_{h\rho}\left(\frac{1-\cos\beta}{2}\right) \tag{49}$$

here, F_1 and F_2 are the circumsolar and horizon brightness coefficients, respectively, and (a) and (b) are the terms that take the incidence angle of the sun on the considered slope into account. The terms (F_1), (F_2), (a) and (b) are computed using the

following equations:

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta z}{180} f_{13}\right)\right] \,\&\, F_2 = f_{21} + f_{22}\Delta + \frac{\pi\theta z}{180} f_{23} \tag{50}$$

$$a = \max(0^\circ, \cos\,\theta \text{ and } b = \max(\cos 85, \cos\theta_z) \tag{51}$$

The coefficients $f_{11}, f_{12}, f_{13}, f_{21}, f_{22}$, and f_{23} were derived based on a statistical analysis of empirical data for specific locations. Two different sets of coefficients were derived for this model [102,103].

5. Comparison techniques of modeling

The relative ability of the different models to predict the solar radiation on horizontal and tilted surfaces was tested. The performance of the individual models was determined by utilizing statistical methods. There are numerous works in literature which deal with the assessment and comparison of daily solar radiation estimation models. The most popular statistical methods are the MBE (mean bias error) and the RMSE (root mean square error). In this study, to evaluate the accuracy of the estimated data, from the models described above, the following statistical estimators were used: MBE, RMSE, MPE (mean percentage error) and the correlation coefficient (R^2), to test the linear relationship between predicted and measured values. For higher modeling accuracy, these estimators should be closer to zero, and the correlation coefficient, (R^2), should approach to 1. The NSE (Nash–Sutcliffe equation) was also selected as an evaluation criterion. A model is more efficient when NSE is closer to 1. However, these estimated errors provide reasonable criteria to compare models but do not objectively indicate whether the estimates from a model are statistically significant. The *t*-test statistic allows models to be compared and at the same time it indicates whether or not a model's estimate is statistically significant at a particular confidence level. So, the *t*-test was carried out on the models to determine the statistical significance of the predicted values [3,10].

5.1. Mean Bias Error (MBE)

To evaluate the accuracy of the prediction data from the models described above, this test provides information on the long-term performance of a model. A low MBE value is desired. A negative value gives the average amount of underestimation in the calculated value. So, one drawback of MBE is that overestimation of an individual observation may cancel underestimation in a separate observation. We can obtain the values of MBE as follows:

$$MBE = \frac{1}{n}\sum_1^n (G_{i,\text{calc.}} - G_{i,\text{meas.}}) \tag{52}$$

and the equation of mean percentage error MPE% is expressed by

$$MPE\% = \frac{1}{n}\sum_1^n \left[(G_{i,\text{calc.}} - G_{i,\text{meas.}})/G_{i,\text{meas.}}\right] 100 \tag{53}$$

The subscript i refers to the ith value of the daily solar irradiation and n is the number of the daily solar irradiation data. The subscripts "calc." and "meas." refer to the calculated and measured daily solar irradiation values, respectively. A percentage error between −10% and +10% is considered acceptable [105].

5.2. Root Mean Square Error (RMSE)

The value of RMSE is always positive, representing zero in the ideal case. The normalized RMSE gives information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the predicted and measured values. The smaller the value is, the better the model's performance is, and the equation of RMSE is as follows [106]:

$$RMSE = \left[\frac{1}{n}\sum_1^n (G_{i,\text{calc.}} - G_{i,\text{meas.}})\right]^{1/2} \tag{54}$$

5.3. The t-test statistic (t)

The tests for mean values, the random variable t with $n-1$ degrees of freedom may be written here as follows [107]:

$$t = [(n-1)(MBE)^2/(RMSE)^2 - (MBE)^2]^{1/2} \tag{55}$$

The smaller the values of *t*-statistic the better the performance of modeling.

5.4. The correlation coefficient (R^2)

In statistics literature, it is the proportion of variability in a data set that is accounted for by a statistical model, where the variability is measured quantitatively as the sum of square deviations. Most often it is defined notationally as [108]

$$R^2 = \sum_{i=1}^n [(Xi - Yi)2] / \sum_{i=1}^n [(Xi - Yi)2] \tag{56}$$

This can also be expressed as

$$R^2 = 1 - \{\sum_{i=1}^n [(Xi - Yi)2] / \sum_{i=1}^n [(Xi - Yi)2]\}\ (0 \le R^2 \le 1) \tag{57}$$

herein, *Xi* and *Yi* are the measurements and model estimates, respectively. A high value of R^2 is desirable as this shows a lower unexplained variation. R^2 is a statistic that gives some information about the goodness-of-fit of a model. In regression, the R^2 coefficient of determination is a statistical measure of how well the regression line approximates the real data points. An R^2 of 1.0 indicates that the regression line perfectly fits the data, which is never valid in any solar radiation estimation model.

6. Results and discussion

The regression equations between (G/G_o) and meteorological variables along with the values of MBE, RMSE, MPE, R^2 and the *t*-test statistics are summarized in Table (1). The empirical correlations for estimation of total solar irradiation on horizontal surface in the form of Eqs. (7)–(15) are proposed for Cairo using the meteorological data during the time period 1990–2010. From the analysis of the measured and calculated values of the total solar irradiation (G), it is clear that, the values of correlation coefficients (R^2) are higher than 0.95 and the values of the RMSE are found in the range 3.13–6.34, thus indicating a good agreement between measured and calculated values of the total solar radiation (G). The negative values of the MPE show that, Eqs. (8), (9), (12), and (13) slightly overestimate the values of the total solar irradiation (G),

Table 1
The relation between (G/G_o), (W/m^2) and metrological variable at Cairo, Egypt, during the time period (1990–2010) by using the empirical correlations models.

Model no.	Regression coefficients			MBE	RMSE	MPE%	R^2	t-test
	a	b	c					
Eq. (7)	0.546	0.356	–	−3.43	5.17	6.55	0.978	5.45
Eq. (8)	0.578	0.389	0.613	−4.43	4.25	−5.34	0.986	4.67
Eq. (9)	0.243	0.456	0.676	−2.34	4.98	−2.92	0.992	4.32
Eq. (10)	0.278	0.675	0.587	−3.87	3.67	2.65	0.965	3.45
Eq. (11)	0.353	−0.439	0.676	2.76	3.16	5.23	0.965	3.67
Eq. (12)	0.316	0.543	0.434	6.56	5.54	−3.76	0.984	6.34
Eq. (13)	−0.487	0.436	−0.687	−4.89	5.89	−2.36	0.973	7.65
Eq. (14)	−0.346	0.489	0.422	−3.21	3.11	6.54	0.962	2.87
Eq. (15)	0.523	0.354	0.632	−2.43	4.35	7.21	0.964	5.65

Table 2
Differences between measured ($G_{d,m}$) and calculated ($G_{d,c}$) values (W/m^2) with the metrological variable at Cairo, Egypt, during the time period (1990–2010).

Model no.	$G_{d,m}$	$G_{d,c}$	MBE	RMSE	MPE%	*t*-test
Eq. (16)	1347	1387	−1.87	2.38	−1.89	2.65
Eq. (17)	1454	1496	3.65	2.91	2.62	3.24
Eq. (18)	1421	1374	2.42	2.24	1.91	1.78
Eq. (19)	1362	1329	1.89	2.47	1.25	1.16
Eq. (20)	1348	1378	−2.75	1.21	1.39	1.14
Eq. (21)	1351	1331	−2.47	2.68	−2.74	2.16

Table 3
Statistical results analysis for Olmo et al., in the present study.

Month	MBE	RMSE	MPE%	R^2	*t*-test
January	29.45	42.24	9.25	0.934	4.89
February	24.82	37.57	6.97	0.958	4.24
March	19.32	31.34	6.34	0.991	3.45
April	18.71	30.24	5.78	0.982	4.74
May	(7.34	28.78	4.87	0.974	4.25
June	9.34	22.76	2.56	0.991	3.14
July	8.84	19.28	3.89	0.984	2.86
August	6.78	22.61	4.46	0.986	3.54
September	8.12	20.87	5.78	0.969	4.37
October	13.24	26.47	6.55	0.986	6.45
November	19.76	33.91	7.46	0.942	5.24
December	32.57	45.18	8.78	0.926	7.47

but, Eqs. (7), (10), (11), (14) and (15) slightly underestimate the values of the global solar irradiation (G). These results indicate a good agreement between the average hourly daily data of the total solar radiation and the other meteorological parameters. Also from Table 1, it is seen that, the values of (*t*-test) change from one model to another model according to the models from Eqs. (7)–(15). Thus the model which gives the smallest values of the *t*-test is then considered as the best model for estimating the total solar irradiation at the selected site with an acceptable error. This means that the models of Eqs. (10), (11) and (14) are a good estimate for the total solar irradiation in the selected location during the time period in the present work.

Table 2 shows the differences between the measured ($G_{d,m}$) and calculated ($G_{d,c}$) values of the diffuse solar radiation along with the values of mean base error (MBE), root mean square error (RMSE), mean percentage error (MPE), and *t*-test statistics. From this table, it is clear that, the low values of the RMSE for all models indicate a good agreement between measured and calculated values of diffuse solar radiation (G_d). The negative values of MPE indicate that the proposed correlations slightly overestimate (G_d). For all models, the absolute values of the MPE indicate very good agreement between measured and calculated values of the diffuse solar fraction (G_d/G) or the diffuse solar transmittance (G_d/G_o) and clearness index K_t, relative number of sunshine hours (S/S_o) and their combination. Also from Table 2, the *t*-test of the model in Eqs. (19) and (20) is given the smallest value, and so it is considered as the best model for estimating the diffuse solar radiation at the selected site with an

Table 4
Average daily values of the mean base error, MBE (%), for global solar irradiation received on an inclined surface at different slopes in the time period 1990–2010.

Slope	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sept.	Oct.	Nov.	Dec.
Isotropic model MBE												
0°	−0.184	−0.356	−0.276	−0.198	−0.256	−0.065	−0.184	−0.148	−0.224	−0.176	−0.132	−0.189
15°	−4.48	−3.87	−2.78	−1.56	−1.56	−0.76	−0.69	−1.54	−2.78	−2.34	−3.79	−3.78
30°	−7.68	−5.77	−4.96	−3.32	−2.43	−1.21	−1.54	−2.61	−4.76	−4.43	−8.55	−7.56
45°	−9.11	−11.42	−7.23	−5.41	−3.43	−2.34	−0.76	−3.76	−5.32	−6.78	−9.23	−6.23
60°	−10.35	−12.54	−8.89	−5.89	−5.34	−4.23	−2.78	−3.55	−6.67	−7.92	−7.65	−8.89
75°	−9.43	−11.67	−9.12	−6.56	−6.1	3.15	1.97	−4.23	−7.84	−8.43	−6.88	−9.56
90°	−8.12	−11.76	−7.34	−5.76	−3.69	1.87	1.54	−2.54	−3.35	−5.54	−7.43	−8.19
Hay's model MBE												
0°	−0.176	−0.223	−0.164	−0.186	−0.245	−0.132	−0.129	−0.165	−0.123	−0.143	−0.154	−0.134
15°	−3.59	−2.87	−2.87	−1.76	−0.69	−0.97	−0.76	−1.43	−1.47	−2.67	−2.87	−2.34
30°	−4.96	−4.23	−3.65	−2.87	−2.21	−0.78	−0.54	−1.78	−3.87	−2.34	−4.12	−3.34
45°	−4.34	−3.87	−4.34	−3.45	−2.78	−1.32	−1.87	−2.54	−3.23	−3.76	−5.54	−4.21
60°	−7.76	−6.95	−5.49	−5.93	−4.54	−2.34	−1.89	−2.68	−3.56	−5.4	−6.43	−6.85
75°	−7.11	−7.54	−6.76	−4.87	−3.32	−1.87	−1.48	−2.87	−3.23	−4.23	−5.67	−5.93
90°	−4.78	−5.84	−5.64	−3.56	−1.47	−1.32	−0.115	−1.91	−2.56	−3.41	−3.65	−4.47
Klucher's model MBE												
0°	−0.187	−0.235	−0.287	−0.154	−0.286	−0.113	−0.149	−0.167	−0.146	−0.178	−0.176	−0.134
15°	−2.65	−2.69	−1.43	−1.0.23	−0.79	−0.89	−0.87	−1.54	−1.43	−2.67	−2.32	−2.86
30°	−4.76	−3.87	−2.23	−2.65	−1.45	0.134	0.46	−1.49	−2.67	−2.87	−3.76	−3.21
45°	−3.89	−2.94	−3.68	−1.76	−1.78	1.56	1.78	−2.76	−2.32	−3.79	−2.95	−3.85
60°	−5.45	−4.87	−3.43	−2.92	−1.59	2.76	1.33	−2.32	−3.54	−4.76	−5.76	−5.21
75°	−4.78	−5.57	−4.34	−3.76	−2.76	1.86	1.74	2.76	−2.76	−3.91	−4.86	−4.56
90°	−3.76	−4.65	−5.23	−2.76	−1.84	1.32	1.65	2.89	−2.45	−3.56	−4.43	−3.86
Perez model MBE												
0°	−0.154	−0.275	−0.234	−0.147	−0.267	−0.124	−0.146	−0.184	−0.124	−0.158	−0.184	−0.132
15°	−2.45	−2.65	−2.49	−1.86	−0.98	−0.86	−1.27	−1.46	−1.34	−2.79	−2.94	−2.24
30°	−2.24	−2.89	−1.98	−2.37	−1.64	−0.49	−0.85	−1.68	−1.79	−1.67	−2.54	−2.41
45°	−3.87	−3.47	−2.41	−2.74	−1.87	−1.48	0.59	−2.24	−1.43	−1.24	−2.24	−2.69
60°	−1.98	−2.76	−2.87	−1.87	−2.45	1.68	1.29	−1.67	−2.78	−2.84	−2.79	−2.23
75°	−2.32	−2.57	−2.89	−3.15	−2.87	2.14	1.84	1.74	−2.14	−2.39	−3.45	−1.98
90°	−4.46	−3.34	−3.45	−2.67	−1.23	1.85	1.47	−2.39	−3.29	−3.47	−4.21	−5.65
Temps and Coulson's models MBE												
0°	2.43	2.68	3.73	2.87	3.48	2.65	2.87	3.76	3.25	4.43	4.35	5.76
15°	3.76	3.32	2.56	3.32	2.34	1.89	3.54	3.97	2.56	3.76	4.87	4.34
30°	−1.78	2.32	2.87	4.87	5.65	6.76	4.78	5.56	3.22	−3.87	−2.43	2.78
45°	−2.56	2.45	3.43	3.76	4.87	5.76	5.23	−4.87	−4.89	2.32	1.95	3.34
60°	−5.76	−5.16	−4.76	2.95	6.56	8.43	4.86	5.21	−3.76	−2.18	−2.86	−2.94
75°	−4.94	−3.89	− −2.98	1.87	2.44	−4.32	−3.54	−3.34	−1.87	−5.76	−3.76	1.65
90°	−5.73	−4.23	−3.54	3.32	7.54	8.36	−4.93	−4.87	4.32	4.98	1.24	−2.78

acceptable error. These results are in good agreement with the previous work performed for other studies [3,57].

The results of the statistical analysis of the relative ability of the Olmo et al. model to determine the solar global irradiation on the inclined surface are presented in (Table 3). The Olmo et al. [3,10,44] model was applied to the database corresponding to the horizontal solar total irradiation to determine values for a south facing surface, tilted at latitude angle for all sky conditions. The hourly daily solar irradiation data have been used in this study and the statistical coefficients have been computed on the basis of the experimental data. From Table 3, we notice that, the mean percentage error (MPE) is in the range between 2.56% and 9.25%, but the values of root mean square error (RMSE) varies from 19.28 to 45.18. Also from this table, we notice that all values of MBE and RMSE in all months are nearest to these values, with the exception of winter months. Normally, these months are subject to heavy rainfall and less solar radiation. The high values of MPE and RMSE and low value of correlation coefficient for these months can be justified. The model provides a good estimation tool for the other months. In general, considering the statistics as a whole, the total solar irradiation data estimated by the Olmo et al. model are in good agreement with the measured values. Therefore, the Olmo et al. model is recommended to estimate the total solar radiation on an inclined surface in this study, due to its accuracy, input requirements and simplicity.

The average hourly daily values of the mean base error, MBE (%), for global solar irradiation received on the inclined surface at different slopes during the time period 1990–2010 are summarized in Table 4. From this table, we notice that, five solar irradiance models are considered in this work: the isotropic model, and the Hay, Klucher's, the Perez, and Temps and Coulson's which are the anisotropic models. For each model, the measured values of diffuse solar radiation and horizontal values of total solar radiation were used to calculate the solar radiation on the surface tilted at different slopes which varies from 0° to 90° above the horizon. The results were compared with the solar irradiances monitored and presented in terms of usual statistics: the mean base error (MBE) and the root mean square error (RMSE). Also from Table 4, it is seen that, the values of MBE vary from −0.065 to −12.54, −0.123 to −7.76, −0.113 to −5.76, −0.124 to −4.46 and 1.24 to 8.43 for the isotropic, Hay, Klucher, Perez and Temps and Coulson's models respectively. The values of MBE results show that, the isotropic, Perez's, Hay′s and Klucher's models substantially underpredict the irradiance incident on an inclined surface, and the Temps and Coulson model considerably overpredicts irradiance incident on an inclined surface on an overall basis.

Table 5 shows the results for south facing surfaces of the root mean square error (RMSE) for different slopes in different models in the present work. From this table, we observed that, the values of root mean square error vary from 0.31 to 31, 0.29 to 21, 0.25 to

Table 5
Average daily values of the root mean square error, RMSE (%), for global solar irradiation received on an inclined surface at different slopes in the time period 1990–2010.

Slope	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sept.	Oct.	Nov.	Dec.
Isotropic model RMSE												
0°	0.79	0.49	0.67	0.84	0.76	0.49	0.31	0.54	0.87	0.67	0.47	0.54
15°	14	15	10	9	7	6	5	6	6.7	5	7	11.3
30°	18	19	13.7	11	8	9	6	7.8	9.2	11	13	19
45°	22	27	25	16	12	13	12	11	5.6	17	24	31
60°	17	21	27	19	19	22	17	14	10	9	17	26
75°	19	25	22	26	26	17	16	18	14	16	25	27
90°	23	31	24	21	17	21	19	14	24	22	30	24
Hay's model RMSE												
0°	0.76	0.49	0.67	0.34	0.72	0.45	0.29	0.39	0.56	0.64	0.32	0.48
15°	9	12	7	6	4	5	3.4	4.2	4.8	5.3	5.2	6.8
30°	11	15	9	8	6.5	3.7	2.3	3.3	6	9	8.4	11.8
45°	9	8	12	5	6	4.3	5	6.2	4.3	7.5	10	17.2
60°	8	14	8.5	9	9	6	3.7	7.8	6.4	6.7	7.8	14
75°	13	16	11	12	7	9	7	10.6	10	12.6	10.4	13.5
90°	16	19	13	9	11.5	10.4	8.7	12	13	15.2	12	12.2
Klucher's model RMSE												
0°	0.49	0.56	0.76	0.37	0.54	0.44	0.25	0.32	0.52	0.42	0.37	0.63
15°	6	7.1	3.9	4.6	3.6	4.3	2.3	3.8	4	4.7	5.8	6.9
30°	9.3	10.5	6.8	5.4	7	5	1.7	4.3	6	7.4	7.4	9
45°	7.3	7.6	9	4	5.2	4.3	4.9	5.6	5.7	8.6	10	12
60°	4.6	9.6	7.2	7	7	6	6	8	8.2	6	7.5	15
75°	8	12	11	10.5	9.3	9.4	8.5	10.7	12.5	10.3	9.6	13.2
90°	13	15.6	8.9	9	11.7	10.3	9.7	12.4	15.4	12	11.5	11.4
Perez model RMSE												
0°	0.44	0.37	0.25	0.19	0.13	0.06	0.08	0.55	0.37	0.34	0.24	0.32
15°	1.65	2.45	2.87	3.65	2.54	1.02	1.57	2.65	2.11	3.76	2.23	2.87
30°	1.89	2.46	2.47	2.86	3.4	1.32	1.34	3.49	2.78	2.23	3.65	4.11
45°	3	3.76	2.54	2.43	1.78	1.12	1.54	3.23	3.23	3.76	3.45	5.23
60°	5	7.89	11	6	5.76	4.65	4.6	6.4	7.45	8.45	7.32	8.56
75°	8.56	10.4	9.4	9.2	7.2	5.78	6	5.8	8.46	7.34	9.43	9.23
90°	11	9.3	8	7.2	5.8	4.21	8.4	7.45	8.56	10.4	11.6	11.4
Temps and Coulson's models RMSE												
0°	3.47	5	4.5	6	7	6.3	10	7	5.5	4.6	5	7.5
15°	5.4	6.3	8.3	9	10.5	9	12	10	7	7	8.6	9
30°	7	7.5	10.4	11	12	10	13	12	9	9	11	11
45°	8.3	9	9.2	12	14	14	15	14	11	10	13	14
60°	10.5	12	15	14	16	21	18	21	18	15	17	17
75°	11.7	13	16	17	19	24	26	26	25	23	19	22
90°	14	15.7	18	20	22	27	30	31	28	30	28	25

Table 6
The statistical results of the models for the south-facing surface at Cairo, Egypt, during the time period from 1990 to 2010.

Model	Abbreviation	Year	*a*	*b*	MBE	RMSE	MPE	R^2	*t*-test
Liu and Jordan	LJ (ISO)	1962	0.154	0.425	12.6	28.7	−8.4	0.957	7.57
Temps and Coulson	TC (ANI)	1977	0.294	0.656	−16.4	33.3	11.8	0.974	8.41
Hay	Ha (ANI)	1979	0.345	0.511	−30.4	9.3	14.6	0.972	6.11
Stevenand Unsworth	SU (ANI)	1980	0.534	0.632	25.8	42.5	16.7	0.981	11.74
Skartveit and Olseth	SO (ANI)	1986	0.674	0.341	−13.6	19.4	−11.7	0.974	6.47
Koronakis	Kr (ISO)	1986	0.165	0.753	−27.9	25.9	13.7	0.962	8.11
Perez et al.	P8 (ANI)	1986	0.281	0.524	18.4	17.9	16.9	0.958	8.87
Reindl et al.	Re (ANI)	1990	0.347	0.524	19.6	8.7	12.4	0.991	4.64
Perez et al.	P9 (ANI)	1990	0.449	0.319	−15.8	19.5	−9.3	0.974	5.55
Tian et al.	Ti (ISO)	2001	0.487	0.384	18.7	24.2	12.8	0.985	7.89
Badescu	Ba (ISO)	2002	0.565	0.376	−22.4	29.5	11.6	0.942	8.47

ISO means isotropic and ANI means anisotropic.

Table 7
The statistical results of the models for the west-facing surface at Cairo, Egypt, during the time period from 1990 to 2010.

Model	Abbreviation	Year	*a*	*b*	MBE	RMSE	MPE	R^2	*t*-test
Liu and Jordan	LJ (ISO)	1962	0.423	0.342	−12.4	34.2	−13.5	0.974	8.45
Temps and Coulson	TC (ANI)	1977	0.312	0.487	−15.2	46.3	16.8	0.949	11.54
Hay	Ha (ANI)	1979	0.396	0.498	−35.6	19.9	19.2	0.987	7.92
Steven and Unsworth	SU (ANI)	1980	0.546	0.343	11.3	47.3	10.8	0.953	13.76
Skartveit and Olseth	SO (ANI)	1986	0.497	0.367	14.7	22.5	−14.9	0.965	6.34
Koronakis	Kr (ISO)	1986	0.411	0.398	−25.7	31.2	17.6	0.971	8.94
Perez et al.	P8 (ANI)	1986	0.511	0.332	16.9	25.8	19.4	0.978	8.23
Reindl et al.	Re (ANI)	1990	0.478	0.322	−19.3	19.7	13.8	0.983	6.64
Perez et al.	P9 (ANI)	1990	0.396	0.456	−12.6	12.4	12.4	0.992	4.76
Tian et al.	Ti (ISO)	2001	0.432	0.325	11.2	30.8	15.8	0.985	6.54
Badescu	Ba (ISO)	2002	0.532	0.387	−22.4	33.6	19.2	0.974	10.76

ISO means isotropic and ANI means anisotropic.

15.6, 0.06 to 11 and 3.47 to 30 for the isotropic, Hay, Klucher, Perez and Temps and Coulson's models respectively. From these values we conclude that, the RMSE values for the fifth model increase as the slope of the collector increases, but remain in a domain of error for which these relations can be applied with good accuracy. Inspecting the results, it is apparent that the models agree quite well with each other during the summer months. They deviate from each other in the winter months, when the effect of the difference in the diffuse solar radiation parameterization is at its maximum. The RMSE results indicate that the anisotropic models (Hay, Klucher and Perez) show similar performance on an overall basis, but isotropic model and Temps and Coulson model exhibit much larger error. In general we confirm that, the observation of the Perez and Klucher models describes the irradiance on inclined plane more accurately than other models. These results in the present work are in good agreement with the other works which are found in [3,108].

Eleven models have been used to evaluate the statistical parameters: mean base error (MBE), root mean square error (RMSE), mean percentage error (MPE), correlation coefficient (R^2) and *t*-test statistics for south-facing and west-facing surfaces in this paper which can be referred to in Tables 6 and 7. The models used were the isotropic models of Badescu (Ba) [94], Tian et al. (Ti) [95], Koronakis (Kr) [96] and Liu and Jordan (LJ) [90], and the anisotropic models of Perez et al. (P9) [104], Reindl et al. (Re) [98], Perez et al. (P8) [103], Skartveit and Olseth (SO) [99], Steven and Unsworth (SU) [100], Hay (Ha) [87], Klucher (Kl) [101], and Temps and Coulson (TC) [102].

The evaluation was carried out on a semi-hourly basis. The total solar irradiation component on the tilted surface was determined from measured horizontal data using different models and compared with the measured tilted data of the same period in the present work. Tables 6 and 7 report a summary of the statistical results of the models for south facing and west facing surfaces in the present study respectively. It is seen from Table 6 that the absolute relative values of the root mean square error (RMSE), for the south facing surface, range from 8.7 to 42.5 for the Hay (Ha) model and the Stevenand Unsworth (SU) model respectively. These results are in good agreement with the values of *t*-test statistics for the same models and the correlation coefficient is clear with the higher value too for self-models. For west-facing surface shown in Table 7, the values of root mean square error range from 12.4 to 47.3 for the Perez et al. (P9) and Temps and Coulson (TC) models respectively. From Tables 6 and 7, we can conclude that the Hay (Ha), Skartveit and Olseth (SO) and Perez et al. (P9) models give the most accurate predictions for the south-facing surface, and Hay (Ha) and Perez et al. (P9) models are perform better estimation for the west-facing surface.

7. Conclusion

The regression equations between (G/G_o) and meteorological variables along with the values of MBE, RMSE, MPE, R^2 and the *t*-test statics are summarized in the present work. Empirical correlations for the estimation of total solar radiation on horizontal surface in the form of Eqs. (7)–(15) are proposed for Cairo using the meteorological data during the time period 1990–2010. From the analysis of the measured and calculated values of the total solar radiation (G), it is clear that, the values of correlation coefficients (R^2) are higher than 0.95 and the values of the RMSE are found in the range 3.13–6.34, thus indicating a good agreement between measured and calculated values of the total solar radiation (G). The models of Eqs. (10), (11) and (14) give a good estimate of the total solar radiation in the selected location during the time period in the present work.

The values of the RMSE for all models in Table 2 indicate a good agreement between measured and calculated values of diffuse

solar radiation (G_d). The negative values of MPE indicate that the proposed correlations slightly overestimate (G_d). For all models, the absolute values of the MPE indicate very good agreement between measured and calculated values of the diffuse solar fraction (G_d/G) or the diffuse solar transmittance (G_d/G_o) and clearness index K_t, relative number of sunshine hours (S/S_o) and their combination.

The values of MBE results show that the isotropic, Perez's, Hay's and Klucher's models substantially underpredict the irradiance incident on an inclined surface, and the Temps and Coulson model considerably overpredicts irradiance incident on an inclined surface on an overall basis, and the RMSE results indicate that the anisotropic models (Hay, Klucher and Perez) show similar performance on an overall basis, but isotropic model and the Temps and Coulson model exhibit much larger error. In general we confirm that, the observation of Perez's and the Klucher models describes the irradiance on an inclined plane more accurately than other models. These results in the present work are in good agreement with the other works in [3,108].

The Hay (Ha), Skartveit and Olseth (SO) and Perez et al. (P9) models give the most accurate predictions for the south-facing surface, and Hay (Ha) and Perez et al. (P9) models perform better estimation for the west-facing surface.

References

[1] Lee Kwanho, Yoo Hochun, Levermore Geoff J. Quality control and estimation hourly solar irradiation on inclined surfaces in South Korea. Renewable Energy 2013;57:190–9.
[2] Pandey Chanchal Kumar, Katiyar AK. A comparative study of solar irradiation models on various inclined surfaces for India. Applied Energy 2011;88:1455–9.
[3] Khalil Samy A, Shaffie AM. Performance of statistical comparison models of solar energy on horizontal and inclined surface. International Journal of Energy and Power 2013;2(1).
[4] Loutzenhiser PG, Manz H, Felsmann C, Strachan PA, Frank T, Maxwell GM. Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. Solar Energy 2007;81:254–76.
[5] Khatib Tamer, Mohamed Azah, Sopian K. A review of solar energy modeling techniques. Renewable and Sustainable Energy Reviews 2012;16:2864–9.
[6] Benghanem M. Optimization of tilt angle for solar panel: case study for Madinah, Saudi Arabia. Applied Energy 2011;88:1427–33.
[7] Gueymard C. Prediction and performance assessment of mean hourly global radiation. Solar Energy 2000;68(3):285–303.
[8] El-Sebaii AA, Trabea AA. Estimation of global solar radiation on horizontal surfaces over Egypt. Egyptian Journal of Solids 2005;28(1).
[9] Ibrahim A, El-Sebaii AA, Ramadan MRI, El-Broullesy SM. Estimation of solar irradiance on inclined surfaces facing south in Tanta, Egypt. International Journal of Renewable Energy Research IJRER 2011;1(1):18–25.
[10] Muzathik AM, Ibrahim MZ, Samo KB, Wan Nik WB. Estimation of global solar irradiation on horizontal and inclined surfaces based on the horizontal measurements. Energy 2011;36:812–8.
[11] Kambezidis HD, Psiloglou BE. The meteorological radiation model: advancements and application. In: Badescu V, editor. Modeling solar radiation at the earth's surface. Springer, Verlag; 2008 ([Chapter 19]).
[12] Psiloglou BE, Kambezidis HD. Performance of the meteorological radiation model during the solar eclipse of 29 March 2006. Atmospheric Chemistry and Physics 2007;7(23):6047–59.
[13] Kadir Bakirci. Correlations for estimation of daily global solar radiation with hours of bright sunshine in Turkey. Energy 2009;34:485–501.
[14] Bahel V, Srinivasan R, Bakhsh H. Solar radiation for Dhahran, Saudi Arabia. Energy 1986;11:985–9.
[15] Bahel V, Srinivasan R, Bakhsh H. Statistical comparison of correlations for estimation of global horizontal solar radiation. Energy 1987;12:1309–16.
[16] Akinoglu BG, Ecevit A. Construction of a quadratic model using modified Ångström coefficients to estimate global solar radiation. Solar Energy 1990;45:85–92.
[17] Fletcher AL. Estimating daily solar radiation in New Zealand using air temperatures. New Zealand Journal of Crop Horticultural Science 2007;35:147–57.
[18] Shafiqur Rehman. Solar radiation over Saudi Arabia and comparisons with empirical models. Energy 1998;23:1077–82.
[19] Rietveld MR. A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine. Agricultural Meteorology 1978;19:243–52.
[20] Alnaser WE. New model to estimate the solar global irradiation using astronomical and meteorological parameters. Renewable Energy 1993;3:175–7.
[21] Trabea AA, Shaltout MAM. Correlation of global solar radiation with meteorological parameters over Egypt. Renewable Energy 2000;21:297–308.
[22] Luis FZ, Lourdes R, Jesus P. Artificial intelligence techniques applied to hourly global irradiance estimation from satellite-derived cloud index. Energy 2005;30:1685–97.
[23] Chegaar M. Chibani, Global solar radiation estimation in Algeria. Energy Conversion and Management 2001;42:967–73.
[24] El-Sebaii AA, Trabea AA. Estimating global solar radiation on horizontal surfaces over Egypt. Egypt Journal of Solids 2005;28:163–75.
[25] Supit I, Van Kappel RR. A simple method to estimate global radiation. Solar Energy 1998;63:147–60.
[26] Halouani N, Nguyen CT, Vo-Ngoc D. Calculation of monthly average global solar radiation on horizontal surfaces using daily hours of bright sunshine. Solar Energy 1993;50:247–58.
[27] Gopinathan KK. A general formula for computing the coefficients of the correlation connecting global solar radiation to sunshine duration. Solar Energy 1988;41:499–502.
[28] Sabziparavar AA, Shetaee H. Estimation of global solar radiation in arid and semi-arid climates of east and west Iran. Energy 2007;32:649–55.
[29] Jacovides CP. Comparative study of various correlations in estimating hourly diffuse fraction of global solar radiation. Renewable Energy 2006;31:2492–504.
[30] Kamali GH, Moradi AI, Khalidi A. Estimating solar radiation on titled surfaces with various orientations: a case study in Karaj (Iran). Theoretical and Applied Climatology 2006;84:235–41.
[31] Muneer T, Saluja GS. A brief review of models for computing solar radiation on inclined surfaces. Energy Conversion and Management 1985;25:443–58.
[32] Diez-Mediavilla M, de Miguel A, Bilbao J. Measurement and comparison of diffuse solar irradiance models on inclined surfaces in Valladolid (Spain). Energy Conversion and Management 2005;46:2075–92.
[33] Notton G, Poggi P, Cristofari C. Predicting hourly solar irradiations on inclined surfaces based on the horizontal measurements: performances of the association of well-known mathematical models. Energy Conversion and Management 2006;47:1816–29.
[34] Martínez-Durbán M, Zarzalejo LF, Bosch JL, Rosiek S, Polo J, Batlles FJ. Estimation of global daily irradiation in complex topography zones using digital elevation models and meteosat images: comparison of the results. Energy Conversion and Management 2009;50:2233–8.
[35] Perez R, Ineichen P, Seals R, Michalsky J, Stewart R. Modeling daylight availability and irradiance components from direct and global irradiance. Solar Energy 1990:44.
[36] Liu BYH, Jordan RC. Daily insulation on surfaces tilted towards the equator. ASRHAE Journal 1961;3:53–69.
[37] Gueymard C. An anisotropic solar irradiance model for tilted surfaces and its comparison with selected engineering algorithms. Solar Energy 1987;38:367–86.
[38] Perez R, Ineichen P, Seals R, Michalsky J, Stewart R. Modeling daylight availability and irradiance components from direct and global irradiance. Solar Energy 1990;44:271–89.
[39] Klucher TM. Evaluations of models to predict insolation on tilted surfaces. Solar Energy 1979;23:111–4.
[40] Hay JE. Calculation of monthly mean solar radiation for horizontal and inclined surfaces. Solar Energy 1979;23:301–7.
[41] Li D, Lam J, Lau C. A new approach for predicting vertical global solar irradiance. Renewable Energy 2002;25:591–606.
[42] Khalil Samy A. Empirical correlations for diffuse solar radiation from global solar radiation and sunshine duration over Egypt. Al-Azhar Bulletin of Science 2007;14(2):203–10.
[43] Khalil Samy A. Evaluation of models for prediction of monthly mean hourly sky-diffuse solar radiation on tilted surface, Cairo, Egypt. International Journal of Pure and Applied Physics 2010;6(3):303–10.
[44] Olmo FJ, Vida J, Foyo I, Castro-Diez Y, Alabos-Arboledas L. Prediction of global irradiance on inclined surfaces from horizontal global irradiance. Energy 1999;24:689–704.
[45] Kreider J, Kreith F. Solar energy handbook. New York: McGraw-Hill; 1981.
[46] Angström A. On the computation of global radiation from records of sunshine. Arkiv for Geofysik 1956;2:471–9.
[47] Sopian K, Othman MYHj. Estimates of monthly average daily global solar radiation in Malaysia. Renewable Energy 1992;2:319–25.
[48] Janjai S, Praditwong P, Moonin C. A new model for computing monthly average daily diffuse radiation for Bangkok. Renewable Energy 1996;9:1283–6.
[49] Sben Z, Tan E. Simple models of solar radiation data for northwestern part of Turkey. Energy Conversion and Management 2001;42:587–98.
[50] Chineke T. Equations for estimating global solar radiation in data sparse regions. Renewable Energy 2008;33:827–31.
[51] Yohanna J, Itodo I, Umogbai V. A model for determining the global solar radiation for Makurdi, Nigeria. Renewable Energy 2011;36:1989–92.
[52] Khatib T, Mohamed A, Mahmoud M, Sopian K. Modeling of daily solar energy on a horizontal surface for five main sites in Malaysia. International Journal of Green Energy 2011;8:795–819.
[53] Abdalla Y, Baghdady M. Global and diffuse solar radiation in Doha (Qatar). Solar & Wind Technology 1985;2:209–12.

[54] Benson R, Paris M, Sherry J, Justus C. Estimation of daily and monthly direct, diffuse and global solar radiation from sunshine duration measurements. Solar Energy 1984;32:523–35.
[55] Trabea A. Analysis of solar radiation measurements at Al-Arish area, North Sinai, Egypt. Renewable Energy 2000;20:109–25.
[56] Top S, Dilma U, Aslan Z. Study of hourly solar radiation data in Istanbul. Renewable Energy 1995;6:171–4.
[57] El-Sebaii A, Al-Hazmi F, Al-Ghamdi A, Yaghmour S. Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. Applied Energy 2010;87:568–76.
[58] Collares-Pereira M, Rabl A. The average distribution of solar radiation: correlations between diffuse and hemispherical and between daily and hourly insolation values. Solar Energy 1979;22:155–64.
[59] Tuller SE. The relationship between diffuse, total and extraterrestrial solar radiation. Solar Energy 1976;18:259–63.
[60] Li H, Ma W, Wang X, Lian Y. Estimating monthly average daily diffuse solar radiation with multiple predictors: a case study. Renewable Energy 2011;36:1944–8.
[61] Mohandes M, Rehman S, Halawani TO. Estimation of global solar radiation using artificial neural networks. Renewable Energy 1998;14:179–84.
[62] Alawi SM, Hinai HA. An ANN-based approach for predicting global radiation in locations with no direct measurement instrumentation. Renewable Energy 1998;14:199–204.
[63] Mihalakakou G, Santamouris M, Asimakopoulos DN. The total solar radiation time series simulation in Athens, using neural networks. Theoretical and Applied Climatology 2000;66:185–97.
[64] Dorvio ASS, Jervase JA, Al-Lawati A. Solar radiation estimation using artificial neural networks. Applied Energy 2002;74:307–19.
[65] Sozen A, Arcaklyˈogblu E, Ozalp M, Kany´ t EG. Use of artificial neural networks for mapping the solar potential in Turkey. Applied Energy 2004;77:273–86.
[66] Fadare D. Modelling of solar energy potential in Nigeria using an artificial neural network model. Applied Energy 2009;86:1410–22.
[67] Lam J, Wan K, Yang L. Solar radiation modelling using ANNs for different climates in China. Energy Conversion and Management 2008;49:1080–90.
[68] Mellit A, Kalogirou S, Shaari S, Salhi H, Arab A. Methodology for predicting sequences of mean monthly clearness index and daily solar radiation data in remote areas: application for sizing a stand-alone PV system. Renewable Energy 2008;33:1570–90.
[69] Reddy K, Ranjan M. Solar resource estimation using artificial neural networks and comparison with other correlation models. Energy Conversion and Management 2003;44:2519–30.
[70] Benghanem M, Mellit A. Radial basis function network-based prediction of global solar radiation data: application for sizing of a stand-alone photovoltaic system at Al-Madinah, Saudi Arabia. Energy 2010;35:3751–62.
[71] Khatib T, Mohamed A, Sopian K, Mahmoud M. Modeling of solar energy for Malaysia using artificial neural networks. In: The 11th WSEAS/IASME international conference on electric power systems, high voltages, and electric machines; 2011. p. 486–9.
[72] Hontoria L, Aguilera J, Zufiria P. An application of the multilayer perceptron: solar radiation maps in Spain. Solar Energy 2005;79:523–30.
[73] Zarzalejo L, Ramirez L, Polo J. Artificial intelligence techniques applied to hourly global irradiance estimation from satellite-derived cloud index. Energy 2005;30:1685–97.
[74] Sen Z. Fuzzy algorithm for estimation of solar irradiation from sunshine duration. Solar Energy 1998;63:39–49.
[75] Elminir Hamdy K. Experimental and theoretical investigation of diffuse solar radiation: data and models quality tested for Egyptian sites. Energy 2007;32:73–82.
[76] Batlles FJ, Olmo FJ, Alados-Arboledas L. On shadow band correction methods for diffuse irradiance measurements. Solar Energy 1995;54:105–14.
[77] WMO. Guide to meteorological observations methods, Tn-8. Geneva, Switzerland: WMO Secretariat, 238; 1990. p.925–32 [chapter 9].
[78] WRC. Sixth international pyreheliometer comparison (IPC VI), 1–18 October. Switzerland: Davos; 1985 (Working report no. 137).
[79] WRC. International pyreheliometer comparison (IPC VII), 25 September–13 October. Switzerland: Davos; 1995 (Working report no. 188).
[80] El-Metwally Mossad. Simple new method to estimate global solar radiation based on meteorological data in Egypt. Atmospheric Research 2004;69: 217–39.
[81] Bird RE, Riordan CJ. Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the Earth's surface for cloudless atmosphere. Journal of Climate and Applied Meteorology 1986;25:87–97.
[82] Spencer JW. Fourier series representation of the position of the Sun. Search 1975;2(5):165–72.
[83] Kreider J, Kreith F. Solar energy handbook. New York: McGraw-Hill; 1981.
[84] Duffie JA, Beckman WA. Solar engineering thermal processes. 2nd ed. New York: Wiley; 1991.
[85] Miguel A, Bilbao J, Aguiar R, Kambezidis H, Negro E. Diffuse solar radiation model evaluation in the north Mediterranean belt area. Solar Energy 2001;70:143–53.
[86] Noorian Ali Mohammad, Moradi Isaac, Kamali Gholam Ali. Evaluation of 12 models to estimate hourly diffuse irradiation on inclined surfaces. Renewable Energy 2008;33:1406–12.
[87] Hay J. Calculation of monthly mean solar radiation for horizontal and tilted surfaces. Solar Energy 1979:23.
[88] Klucher M. Evaluation of models to predict insolation on tilted surfaces. Solar Energy 1979;23:111–4.
[89] Yadav Amit Kumar, Chandel SS. Tilt angle optimization to maximize incident solar radiation: a review. Renewable and Sustainable Energy Reviews 2013;23:503–13.
[90] Liu B, Jordan R. Daily insolation on surfaces tilted towards the equator. Transactions of ASHRAE 1962:67.
[91] Hottel HC, Woertz BB. Evaluation of flat-plate solar heat collector. Transactions of ASME 194291.
[92] Liu BYH, Jordan RC. The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation. Solar Energy 1960;4(3):1–19.
[93] Duffie JA, Beckman WA. Solar engineering of thermal processes. second ed. New York, Chichester, Brisbane, Toronto, Singapore: John Wiley & Sons; 1991.
[94] Badescu V. A new kind of cloudy sky model to compute instantaneous values of diffuse and global irradiance. Theoretical and Applied Climatology 2002;72:127–36.
[95] Tian YQ, Davies-Colley RJ, Gong P, Thorrold BW. Estimating solar radiation on slopes of arbitrary aspect. Agricultural and Forest Meteorology 2001;109:67–77.
[96] Koronakis PS. On the choice of the angle of tilt for south facing solar collectors in the Athens basin area. Solar Energy 1986;36:217.
[97] Reindl DT, Beckmann WA, Duffie JA. Diffuse fraction correlations. Solar Energy 1990;45(1):1–7.
[98] Reindl DT, Beckmann WA, Duffie JA. Evaluation of hourly tilted surface radiation models. Solar Energy 1990;45(1):9–17.
[99] Arvid Skartveit, Asle Olseth Jan. Modelling slope irradiance at high latitudes. Solar Energy 1986;36(4):333–44.
[100] Steven MD, Unsworth MH. The angular distribution and interception of diffuse solar radiation below overcast skies. Quarterly Journal of the Royal Meteorological Society 1980;106:57–61.
[101] Klucher T. Evaluation of models to predict insolation on tilted surface. Solar Energy 1979;23:114.
[102] Temps RC, Coulson KL. Solar radiation incident upon slops of different orientations, 19; 1977. p. 179–84.
[103] Perez R, Seals R, Ineichen P, Stewart R, Menicucci D. A new simplified version of the Perez diffuse irradiance model for tilted surfaces. Solar Energy 1987;39 (3):221–32.
[104] Perez R, Ineichen P, Seals R, Michalsky J, Stewart R. Modeling daylight availability and irradiance components from direct and global irradiance. Solar Energy 1990;44(5):271–89.
[105] Robaa SM. Evaluation of sunshine duration from cloud data in Egypt. Energy 2008;33:785–95.
[106] Glover J, McCulloch JS. The empirical relation between solar radiation and hours of sunshine. Journal of Royal Meteorological Society 1958;84:172–5.
[107] Iqbal M. An introduction to solar radiation. New York: Academic Press; 1983.
[108] Elminir Hamdy K, Ghitas Ahmed E, El-Hussainy F, Hamid R, Beheary MM, Abdel-Moneim Khaled M. Optimum solar flat-plate collector slope: case study for Helwan, Egypt. Energy Conversion and Management 2006;47 (5):624–37.